CRREL REPORT 93-1

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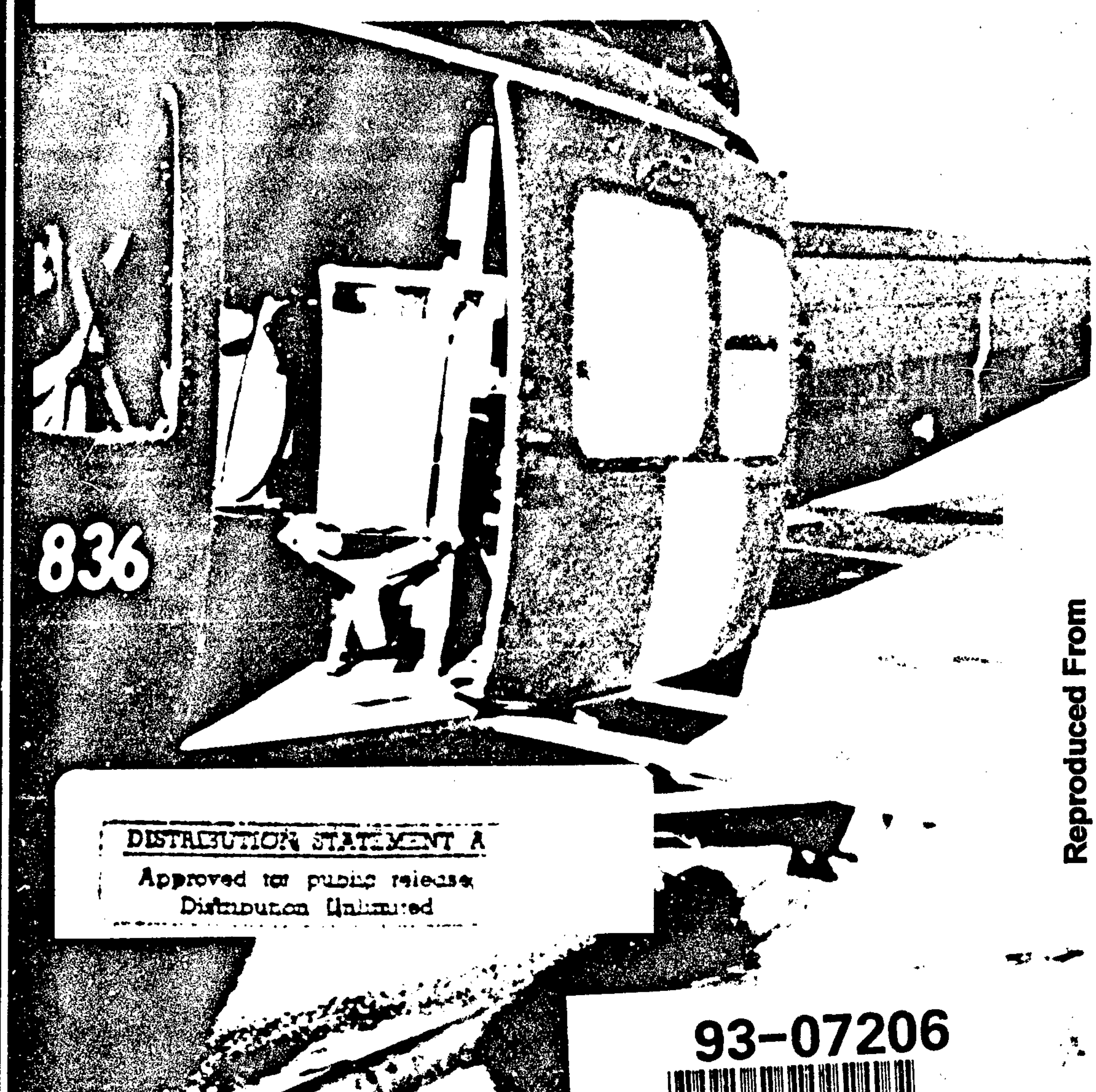
Development of an Airborne MMW FM-CW Radar for Mapping River Ice

Norbert E. Yankielun, Michael G. Ferrick
and Patricia B. Weyrick

January 1993



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Abstract

Analyses of a river's freezeup ice cover stability and its breakup rely on detailed knowledge of the cover's thickness and the variability of that thickness. A high-resolution, millimeter wave (26.5- to 40-GHz) Frequency Modulated-Continuous Wave radar with real-time data acquisition and digital signal processing and display capability was deployed from a low-flying (3–10 m) helicopter to continuously acquire, process and display data during an ice thickness profiling survey of a 24-km study reach. A nominal sheet ice thickness of 50 cm, occasional areas of new ice sheet as thin as 5 cm, open leads, and massive ice accumulations on the order of 5 m thick were encountered. Radar profiling data agreed with ground truth from borehole measurements of the sheet ice, and provided a more detailed view of the ice conditions than that obtained from a low altitude video survey. The radar system provided rapid, safe and accurate data acquisition, allowing detailed mapping of the ice conditions throughout the reach.

Cover: Radar mounted on helicopter.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Standard Practice for Use of the International System of Units (SI)*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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PREFACE

This report was prepared by Dr. Norbert E. Yankielun, Research Associate from Dartmouth College, Michael G. Ferrick, Hydrologist, and Patricia B. Weyrick, Physical Science Technician, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by Contract No. DACA 89-90-K-0003, *Millimeter Radar Remote Sensing of Freshwater Ice Thickness*, with Dartmouth College, Hanover, New Hampshire, and by DA Project 4A762784AT42, *Cold Regions Engineering Technology*; Task CS; Work Unit 001, *River Ice Mechanics for Combat Engineering*.

Technical review was provided by Dr. S. Arcone and G. Koh, both of CRREL.

Development of an Airborne MMW FM-CW Radar for Mapping River Ice

NORBERT E. YANKIELUN, MICHAEL G. FERRICK, AND PATRICIA B. WEYRICK

INTRODUCTION

For at least the last 25 years, considerable effort has been expended on applying radar for geophysical profiling of freshwater ice, sea ice and ground (Page and Ramseier 1975, Batson et al. 1984, Wills 1987, Riek 1988). The majority of the effort, to date, has been with impulse radar at frequencies less than 1 GHz, giving an ability to resolve ice thicknesses in the range of 10 to 20 cm (Page and Ramseier 1975, Arcone and Delaney 1987, Riek 1988, Arcone 1991). Microwave (7–12 GHz) approaches have also been tried, using the impulse technique to reach about the same resolution (Chudobiak et al. 1978).

The Frequency Modulated-Continuous Wave (FM-CW) technique has been applied at the X-band to measure freshwater ice thicknesses down to 14 or 15 cm (Venier and Cross 1975), for geophysical remote sensing applications (Wittmann and Stoltenberg 1981) and for snow stratification investigations at 8 to 12 GHz (Ellerbruch and Boyne 1984, Gubler and Hiller 1984). Recently, a high-resolution, continuous profiling capability has been demonstrated on river and lake ice (Yankielun 1992, Yankielun et al. 1992) with a prototype airborne millimeter-wave (MMW) FM-CW radar system, capable of resolving a minimum ice thickness of 3 cm ±10%. While the capability to profile freshwater sheet ice has been well established, the lack of simultaneous location information has prevented the construction of ice cover maps from these data. Also, radar thickness measurement of rubble or brash ice jams (Daly and Arcone 1989) remains an unsolved problem.

Our study reach of the Connecticut River (Fig. 1) can have severe and highly variable ice conditions. Midwinter thaws accompanied by significant rainfall and snowmelt occur in most years. These events

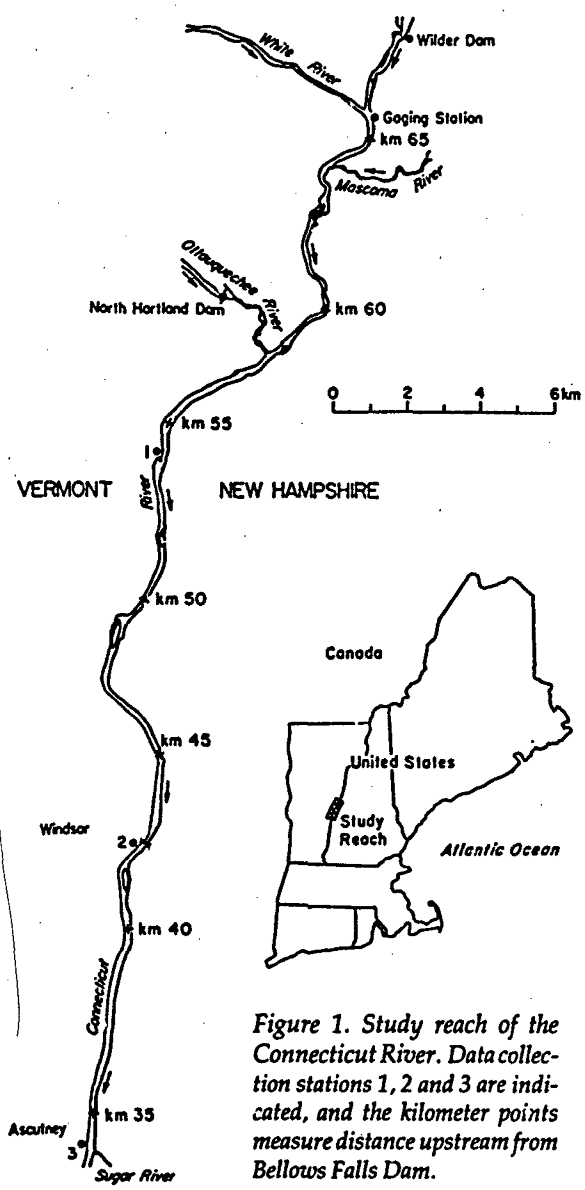

Figure 1. Study reach of the Connecticut River. Data collection stations 1, 2 and 3 are indicated, and the kilometer points measure distance upstream from Bellows Falls Dam.

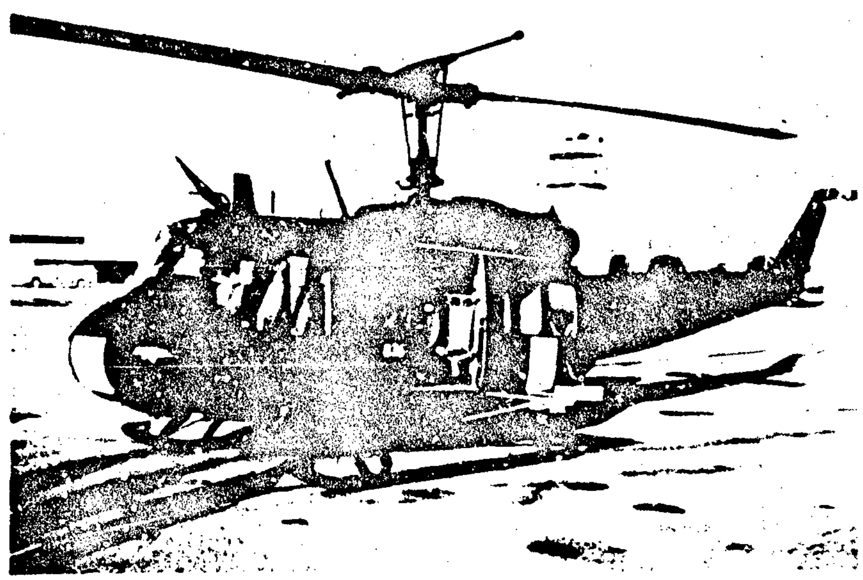

Figure 2. Helicopter-mounted radar system ready for deployment. The radar system front-end mounted to hard points on the helicopter is visible.

cause frequent ice runs on the freely flowing White River, and subsequent ice jams in the study reach. Under normal flow conditions, the river is controlled by Wilder Dam, which produces peak-demand power. During the winter the dam release can surge from 20 to 300 m^3/s in minutes, as often as twice a day. The formation, breakup and jamming of an ice sheet respond to the river flow and to flow and water level fluctuations. Subsequent cyclical wetting and drying of these ice accumulations during sub-freezing air temperatures causes freeze bonding of brash ice and the development of ice formations up to an order of magnitude thicker than a sheet grown in still water.

Modeling ice breakup in this reach (Ferrick et al. 1988) relies on detailed knowledge of the ice thickness and thickness variability. Studies aimed at minimizing the ice produced in the river by flow control during the freezeup (Ferrick and Mulherin 1989) require the knowledge of the thickness of newly formed ice to quantify correctly its response to flow surges. Here, we discuss the results of an ice profiling survey of the Connecticut River, on 2 March 1992, conducted using an FM-CW radar operating in the 26.5- to 40-GHz frequency range, flying at approximately 15 to 20 km/hr at 3 to 10 m above the ice surface. Figure 2 shows the radar system mounted in a helicopter ready for deployment.

The survey was made in the early morning, with temperatures below –10°C and an ice surface that was cold and dry with little or no visible snow cover. The river flow was very low, and much of the ice rubble was grounded on the bed. The radar provided a continuous record of sheet ice thickness. As expected, no definitive indication of rubble thickness was possible, primarily because of signal attenuation caused by surface and volume scattering by the rubble. However, the combination of radar returns synchronized with an audio description of the ice and the helicopter location yielded a detailed one-dimensional map of the ice conditions.

FM-CW RADAR

In an FM-CW system (Fig. 3), the output of a MMW linear Voltage Controlled Oscillator (VCO) is transmitted toward the target. The energy reflected from the target, delayed by the round-trip propagation time $2t_p$, is mixed with a sample of the sweep rf (radio frequency) oscillator output. The difference frequency F_r is proportional to the target range and can be determined using spectral analysis techniques. With two primary scattering boundaries, as in the case of the air/ice and the ice/water interfaces found on a sheet of ice floating on water,

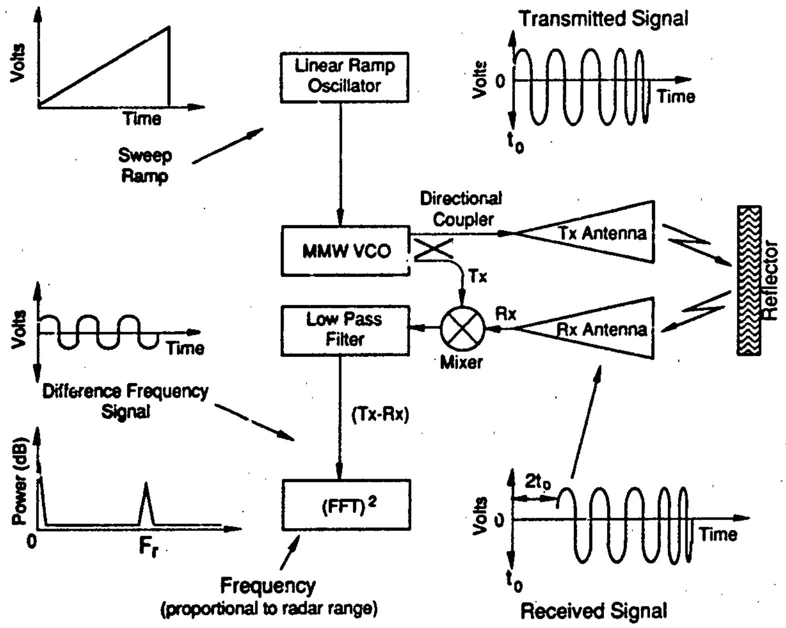

Figure 3. Block diagram of FM-CW radar system.

ideally there will be two distinct frequency components, one from each of the interfaces. The difference between these two frequencies is proportional to the distance between the two interfaces.

Figure 4 shows an example of the processed FM-CW radar return. The broader the swept bandwidth is, the greater is the ability to resolve the two difference frequencies. For the system discussed here, the bandwidth is 26.5 to 40 GHz, as available from the VCO. Distance is calibrated in terms of frequency according to the relation

$$\text{Range to ice surface (m)} = \frac{(F_{r1})(t_{swp})c}{2(BW)(n_{air})} \quad (1)$$

where F_{r1} = difference frequency ascribable to air/ice interface reflection (Hz)
t_{swp} = FM-CW sweep time (s)
c = velocity of light in a vacuum (m/s)
BW = FM-CW swept bandwidth (Hz)
n_{air} = index of refraction of air = 1.

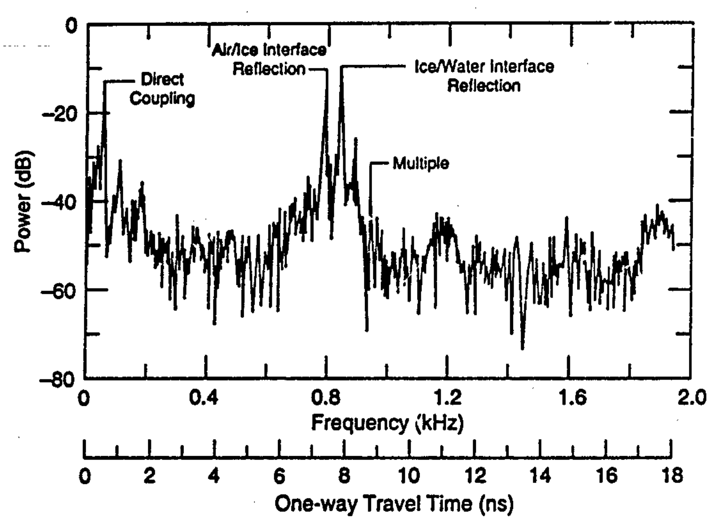

Figure 4. Typical MMW FM-CW DSP-processed radar scan.

Ice thickness is calibrated from the separation of the two difference frequencies according to the relation

$$\text{Ice thickness (m)} = \frac{(F_{r2} - F_{r1})(t_{swp})c}{2(B\ W)(n_{ice})} \quad (2)$$

where F_{r2} = difference frequency attributable to ice/water interface reflection

n_{ice} = index of refraction of freshwater ice = 1.78 (Cumming 1952).

SYSTEM CONFIGURATION

The radar data acquisition and Digital Signal Processing (DSP) computer system (Fig. 5) is fully housed in a 55- × 60- × 75-cm water-resistant and shockproof case weighing less than 25 kg and is powered by a 24-V, 25 A-hr battery providing more than 2 hours of remote field or airborne operation. The front-end of the radar is housed in a separate waterproof aluminum enclosure containing the waveguide directional couplers, diode mixer, linear MMW VCO and a low-noise voltage amplifier. The front-end assembly is mounted to external hard points on the helicopter for airborne profiling. Two coaxial cables carrying the linear sweep ramp and radar output signals interconnect the radar front-end to the computer system. Operating power for the radar front-end is provided by way of a third cable. All data acquisition, monitoring, display, digital storage and radar control functions are performed by seven off-the-shelf dedicated-function computer cards installed in the 33-MHz 80386 DOS-based computer with an 80387 math coprocessor, a conventional 40-megabyte hard-drive and 4 megabytes of RAM. A Bernoulli removable-platter, 44-megabyte drive is available for in-flight use because it is less susceptible to failure at high vibrations or high g-forces.

Continuous real-time data and a synchronization signal are stored on two channels of a Digital Audio Tape (DAT) recorder for later playback and processing. The DAT recorder also provides event timing and a voice channel, permitting a descriptive narrative to be recorded in concert with the acquired radar data. A 20-MHz, 12-bit, dual-channel digital oscilloscope card permits real-time moni-

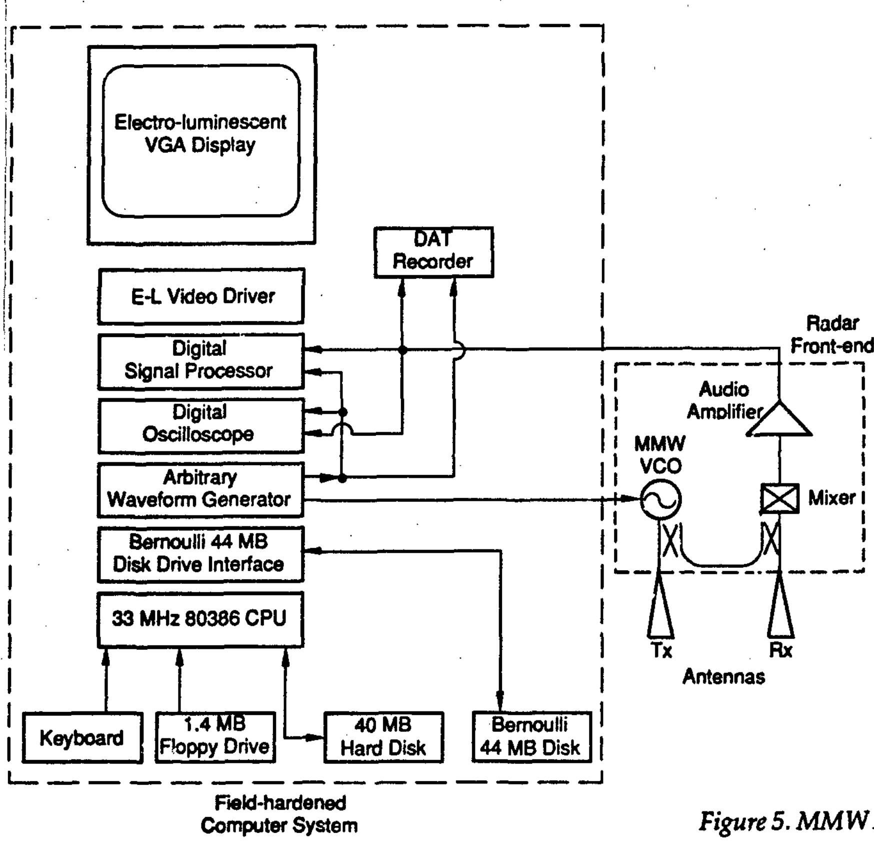

Figure 5. MMW FM-CW radar system setup.

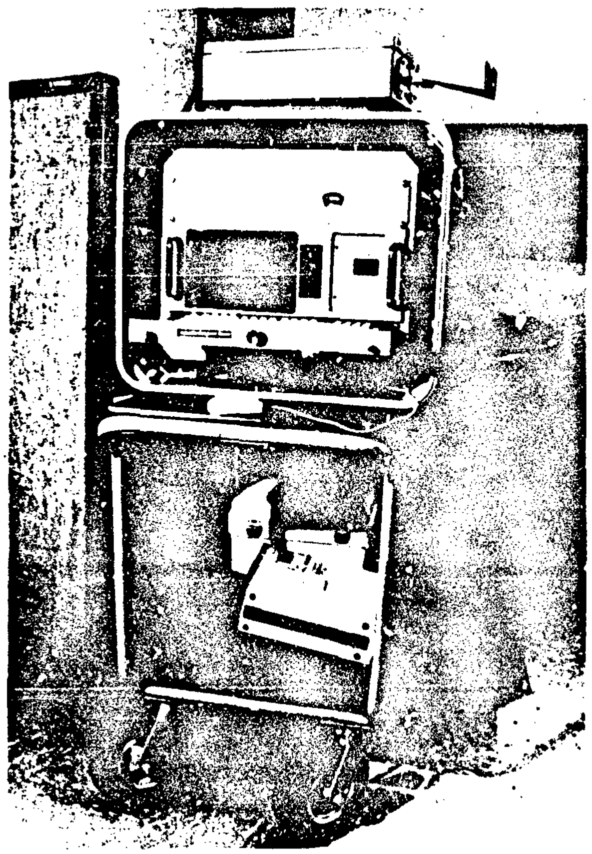

Figure 6. Components of a MMW radar system.

toring of various system signals on the computer display without affecting on other in-progress data acquisition or processing functions. A Spectrum, Inc., DSP card acquires dual-channel, 16-bit data to a maximum rate of 200 kHz and processes the digital signal using the Hyperception, Inc., Hypersignal Workstation DSP software as a driver. A dual channel arbitrary waveform generator is programmed to provide the linear ramp 0- to 10-V sweep signal to frequency modulate the MMW linear VCO and a trigger pulse for system synchronization. An Electro-Luminescent (EL) video driver card provides an interface between the computer system and an EL orange-on-black video display that is VGA-compatible. This display is lightweight, uses low power, has high contrast, is immune to vibration and is well suited for field use.

The system is controlled directly by computer keyboard input. The oscilloscope and arbitrary waveform generator have "pop-up" window displays that can be viewed, modified and hidden by a "CONTROL + character" keystroke. Figure 6 is a photograph showing all major system components, including the radar front-end with dual horn antennas in a waterproof aluminum box (top), the radar data acquisition and DSP computer system in its case (middle), and the DAT recorder and 24-Vdc battery box (bottom). Figure 7 is a photograph of a typical "waterfall" screen display of actual acquired and processed

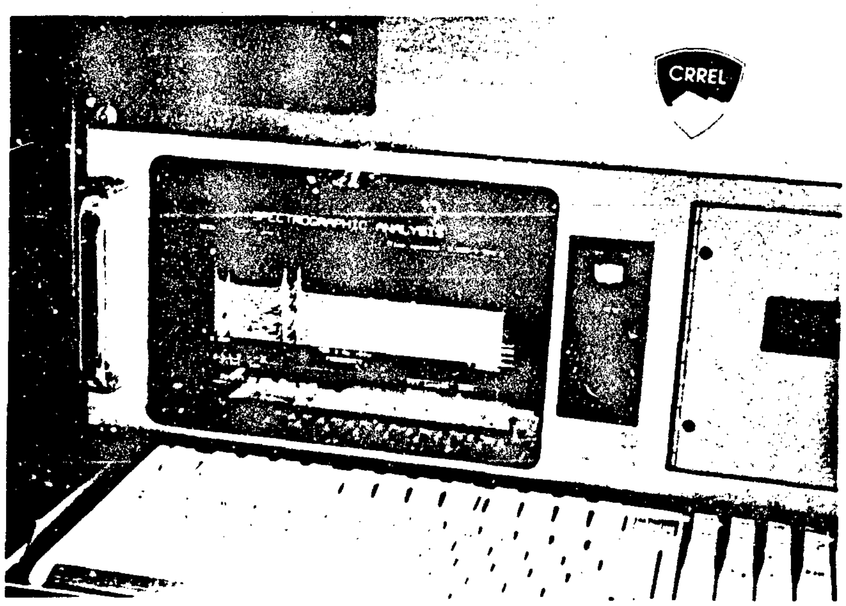

Figure 7. Computer screen with typical waterfall type data display.

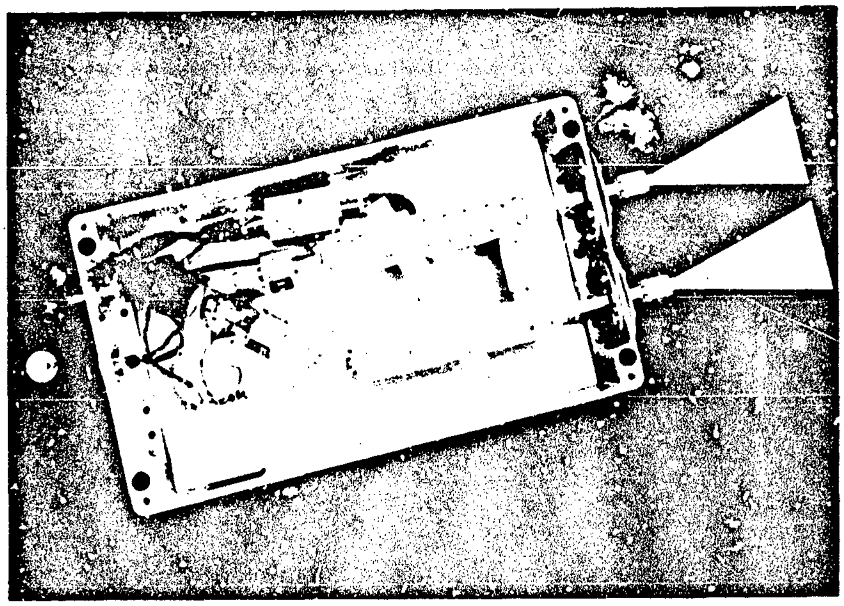

Figure 8. Radar front-end and antenna components.

data from ice thickness measurements. Figure 8 is a photograph of the radar front-end components, with the dual horn antennas (right), waveguide directional couplers and isolators (middle), MMW linear VCO (upper left), and audio amplifier (middle right) visible. A 15-cm rule is shown for scale.

After completion of a survey, the raw radar data, recorded on the DAT recorder, were processed in the laboratory and displayed (as shown in subsequent figures) using a Macintosh II computer equipped with a Spectral Innovations, Inc., DSP coprocessor. Each radar scan was digitized to provide 2048 time series samples, transformed into a power spectrum, processed with a Hanning window algorithm to suppress the effect of spectral sidelobes, which might otherwise mask lower level signals, and displayed in a continuous spectrographic form. In a spectrogram, discrete signal magnitude quanta are represented by a range of color or gray scale. With 16-shade gray scale graphics, as illustrated, this results in maximum signal magnitudes appearing as black and intermediate levels appearing as lighter shades of gray. Below a preset magnitude threshold, all is shown as white. The levels can be set in the DSP software to display clearly both the air/ice and ice/water interfaces. Multi-color spectrographic display provides significantly greater graphical resolution than is possible with monochromatic display, indicating intermediate levels of signal intensity on a 256-shade color gradient.

RESULTS

A spectrogram of a radar profile segment, approximately 2 km long, of the study reach is shown in Figure 9. Here, a variety of ice conditions en-

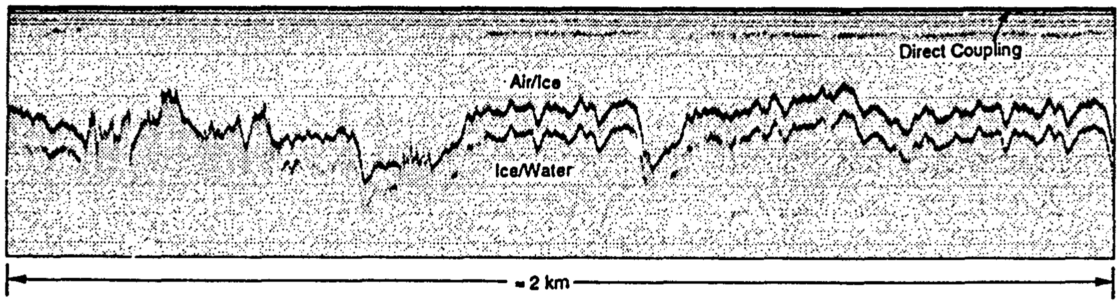

Figure 9. Radar profile segment of 2 km of the study reach showing a variety of ice conditions encountered.

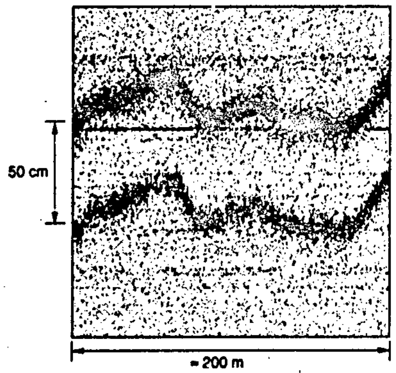

Figure 10. Spectrogram of sheet ice.

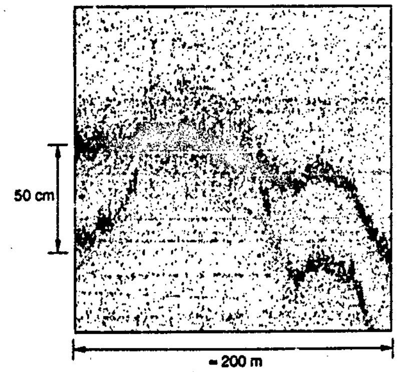

Figure 12. Spectrogram of an open lead surrounded by sheet ice.

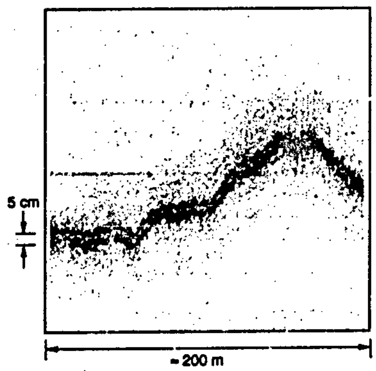

Figure 11. Spectrogram of thin sheet ice.

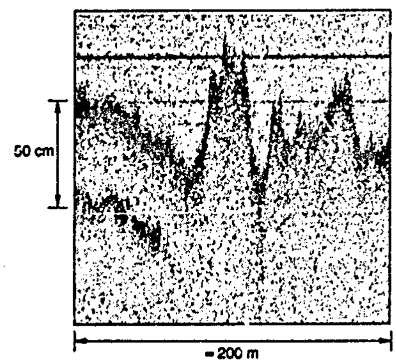

Figure 13. Spectrogram of transition from sheet ice to rubble.

countered during the survey, including smooth sheet ice and rubble fields, is visible. The dark, horizontal bands at the top of the figure are caused by radar reflections from antenna direct coupling to the atmosphere. Further down the figure, two paired traces are visible. The first of these traces indicates the air/ice interface and the second (lower) trace indicates the corresponding ice/water interface. The vertical distance between these two traces is proportional to sheet ice thickness. Rubble fields are indicated by the presence of only a single trace from the air/ice interface reflection. Severe scattering within the rubble precludes a bottom reflection. In-flight helicopter altitude variations cause the spectrogram to have a wavy appearance.

Figure 10 shows a typical spectrographic display from a smooth, freshwater ice sheet, nominally 50 cm thick. Here, since both top and bottom surfaces of the ice sheet are relatively smooth, strong reflections from both interfaces are visible. This display and each of the subsequent spectrographic segments represent close-up views of radar reflections from ice features along approximately 200 m of horizontal displacement on the river survey path.

Figure 11 shows the response from thin, new ice, nominally 5 cm thick, that formed on areas of open water when nighttime air temperatures were below −15°C. This new, smooth ice sheet permits well-defined top and bottom interface reflections and is some of the thinnest ice cover encountered during this airborne survey.

The tapering transition from a 50-cm-thick ice sheet to an open lead and back to sheet ice is shown in Figure 12. Here, the high reflectivity of the air/water boundary results in a strong radar return, causing this region of the spectrogram to appear broader than the air/ice or ice/water boundary traces. For given spectrogram quantization thresholds, the larger a reflection is in magnitude, the further down the pulse skirts intersect the threshold and the broader the appearance of the resulting trace.

An abrupt transition from 50-cm-thick sheet ice into a rubble field is shown in Figure 13. There is a

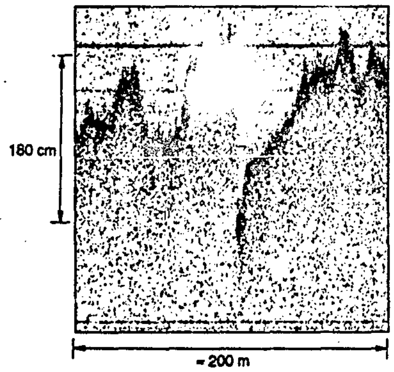

Figure 14. Spectrogram of rubble field relief.

small zone (middle of figure) between the smooth ice sheet and the rubble where a strong surface return is present but no bottom return is evident. This is possibly attributable to ice rubble trapped beneath the smooth-surfaced sheet, producing a strong return from the air/ice boundary and substantial scatter at the ice/water boundary. In the region of rubble ice, the radar return has a characteristic "fuzzy" appearance because of scattering from the rough surface. The MMW radar signal was severely scattered within the rubble and therefore bottom returns were not visible. Scattering from within a rubble mound is seen as the "cloudy" area beneath the surface return.

The surface relief distortion caused by in-flight altitude variations does not normally permit accurate rubble field relief measurements owing to a lack of a constant altitude reference; however, at the center of Figure 14, an instantaneous (scan-to-scan) variation in rubble field relief of approximately 180 cm is shown. In normal flight, the vertical displacement of the helicopter is minimal during each radar inter-scan time (on the order of tens of milliseconds) and, therefore, the instantaneous vertical displacement indicated in the figure is predominantly attributable to an actual surface variation in the rubble relief.

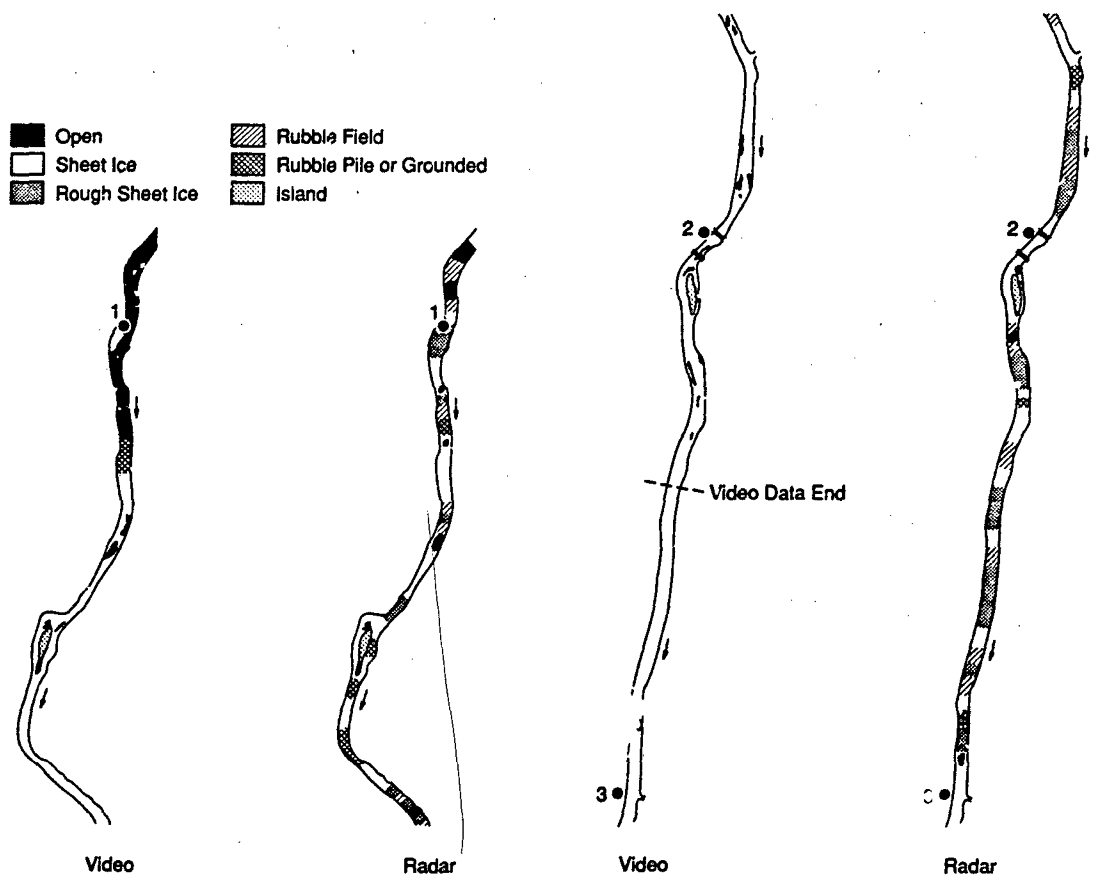

Figure 15. Ice maps developed for the study reach from radar and video records (data collection stations 1, 2 and 3 are indicated).

The ice conditions through the study reach were mapped from the radar returns and the synchronized audio location records. This map is presented in Figure 15, together with a comparable map developed from a video survey made 4 days later with low-altitude aircraft. The differences between maps near station 1 reflected changes in the ice cover caused by a controlled breakup of the river (Ferrick and Mulherin 1989). Farther downstream the map differences are a result of the capabilities of the method of data acquisition. The radar data were obtained along a single flight line, and the ice maps depict this one-dimensional sampling. However, the radar survey provided a detailed view of the ice conditions that was not available in the video record. The video data detailed the open water areas in two dimensions. The simultaneous recording of video and radar data from the same helicopter may have extended the radar maps into two dimensions.

CONCLUSIONS

Continuous, high-resolution airborne profiling of river ice with MMW radar can provide an accurate survey of cold, dry ice conditions both rapidly and safely. The MMW radar system permitted detailed mapping of sheet and rubble ice throughout our study reach. The capability to record simultaneous event time, voice information and radar data on the DAT recorder enhanced the survey record with a descriptive narrative of ice conditions and identification of physical landmarks along the survey path. Ice thicknesses less than 5 cm were resolved with the MMW radar. This capability provides data that are necessary for ice management studies looking at the stability of thin ice covers subjected to surging flow.

As expected, MMW radar probing of rubble accumulations on the order of several meters thick was subject to severe scattering. Future enhancements to this survey tool include simultaneous airborne deployment of a very high frequency (VHF), 50–500 MHz FM-CW radar with the existing MMW system, thus improving profiling capability over brash ice jams while maintaining high-resolution profiling of ice sheets. This capability will provide a better overall view of the range of ice conditions encountered. Video taken in concert with airborne radar profiling will extend the data record along the survey line to better define ice features in two dimensions. A Global Positioning System (GPS), providing longitude and latitude data, will be interfaced with the radar to permit a more precise mapping of the river survey path.

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13. ABSTRACT (*Maximum 200 words*)

Analyses of a river's freezeup ice cover stability and its breakup rely on detailed knowledge of the cover's thickness and the variability of that thickness. A high-resolution, millimeter wave (26.5- to 40-GHz) Frequency Modulated-Continuous Wave radar with real-time data acquisition and digital signal processing and display capability was deployed from a low-flying (3–10 m) helicopter to continuously acquire, process and display data during an ice thickness profiling survey of a 24-km study reach. A nominal sheet ice thickness of 50 cm, occasional areas of new ice sheet as thin as 5 cm, open leads, and massive ice accumulations on the order of 5 m thick were encountered. Radar profiling data agreed with ground truth from borehole measurements of the sheet ice, and provided a more detailed view of the ice conditions than that obtained from a low altitude video survey. The radar system provided rapid, safe and accurate data acquisition, allowing detailed mapping of the ice conditions throughout the reach.

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